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PYROTECHNIC FLARE SPECTROSCOPY III

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RESEARCH AND DEVELOPMENT DEPARTMENT

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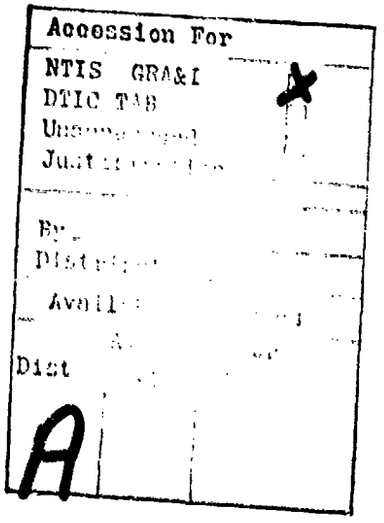
FORWARD

This paper was prepared for presentation at the annual NAVAIR review of its sponsored research programs in the field of Energy Conversion (non-propulsive aspects) to be held on 8-10 November, 1972, at the Naval Weapons Center, China Lake, California. The work is sponsored by the Research and Technology Group of the Naval Air Systems Command. Dr. Hyman Rosenwasser is the program Manager in NAVAIR.

The progress report for fiscal year 1971 is contained in RDTN No. 201, Pyrotechnic Flare Spectroscopy, Naval Ammunition Depot, Crane, Indiana, 1 November 1971.



PYROTECHNIC FLARE SPECTROSCOPY

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Scientific Background

Illuminating flares are typically made from a mixture of magnesium, sodium nitrate, and a binder. Light is emitted from these flares at a luminous efficiency of about 50,000 candle-seconds/gram. To satisfy the continuing need to generate light more efficiently, the specific objective of this work is directed toward determining the mechanisms by which light is emitted from illuminating flames, the new knowledge providing the basis for future improvements.

The approach being taken is to study emission spectra of illuminating flames tested at various pressures and with different formulas. The aim of these studies is to relate the experimental observations to some set of parameters which characterizes the state of the flame. Theoretical models and prediction equations are being developed which predict the flare output based on knowledge of the flare formula, flare size, and ambient pressure.

Status

The initial experiments to obtain spectra for validation of the theoretical model and the prediction equations have been completed. The computation of the sodium atom density in the experimental flames and computation of the effective adiabatic flame temperature are finished. The preliminary computation of the theoretical spectra using a local thermal equilibrium, LTE, radiative transfer model shows good agreement with the experimental spectra. Details of the basis for this work and interim reports of recent phases are included in references 1 through 4.

Significance of the Study

This research is intended to provide a better understanding of how light is generated by a pyrotechnic illuminating flare. Several significant advances have come about from this work:

1. Atomic sodium in the illuminating flame was shown[1] to be the dominant emitter in the visible region.

2. The major portion of the total flux radiated by flames from magnesium-sodium nitrate flares is due to emission from broadened sodium D lines, the broadening being a function of pressure, sodium atom density, and related parameters.

3. The LTE radiative transfer model, as we have constructed it, can be used to predict illuminating flame output with knowledge only of the flare formula, flare size, and ambient pressure at which

the flare is burned. The model can readily be generalized to predict the spectral output of flares containing any of the alkali metals making the model useful for a variety of pyrotechnic problems in addition to illumination.

Progress (July 1971 - October 1972)

Three groups of flares were made with the following formulas:

	Group 22	Group 25	Group 26
Magnesium	44.0%	40.40%	40.04%
Sodium Nitrate	51.5%	5.15%	0.515%
Potassium Nitrate		49.95%	54.945%
Binder	4.5%	4.5%	4.5%

The distinguishing feature is the change in sodium nitrate concentration by substitution of potassium nitrate. Spectra were obtained of the emission from these flares while burning at pressures between 760 and 6 torr. A summary of the spectral data is provided in Figure 1. The figure clearly shows the change in spectral distribution of the flux radiated by the flame as the ambient pressure and/or sodium atom density change. It is this feature which is of primary interest.

By visual inspection of Figure 1, we can observe the influences that sodium atom density and ambient pressure have on the distribution of emitted power. First, for Group 26 at 30 torr, we see two lines in emission separated 6 Å, each showing an absorption region at their respective line centers. The rather narrow lines are due to emission

from the sodium D_2 and D_1 lines. As the pressure is increased from 30 torr to 75 to 150 to 225 torr, we observe the broadening of each of the lines with the absorption region at line center getting wider and deeper. As the pressure increases and the broadened lines overlap in an increasing amount, we see a coalescence of the two lines halfway between them, becoming completely filled near 300 and 630 torr. As the pressure increases to 760 torr, the lines and absorption region broaden even further causing the region between the lines to become less intense in relation to the maxima on either side of the D line center frequency.

To obtain input values for effective flame temperature and sodium atom density for use in the radiative transfer model we used the computational procedures described by Gordon and McBride[5]. The results, estimating a 30 percent enthaply loss, are given in Figure 2. The values are used to solve the LTE case of the differential equation[6] for radiative transfer,

$$dI_\nu/d\tau = \phi_\nu(a)\ [I_\nu - B_\nu(T)] \qquad (1)$$

where ν is frequency, B is the Planck function, T is temperature, τ is optical thickness, ϕ is the 2-line Voigt profile, the Voigt profile a is the ratio of the sum of the resonance and collisional half widths to the Doppler half width, and I is the emergent intensity in a direction normal to the flame. Integration of equation (1) to find the emergent

intensity on the surface of the flame ($\tau = 0$) with no energy incident on the rear of the flame yields,

$$I_\nu = \phi_\nu(a) \int_{t=0}^{t=z} B_\nu(T) \exp(-\tau(t)\ \phi_\nu(a))\ dt \qquad (2)$$

where Z is the thickness of the flame (cm).

A parabolic temperature gradient is constructed in the model using the computed temperature given in Figure 2 as the temperature at flame center. The boundary temperature is taken to be 1200°K. The appropriate Planck value is computed as a function of frequency and temperature through the flame medium. A two-line Voigt profile, weighted for line oscillator strength, is constructed numerically to approximate the line distribution due to resonance and collisional broadening. The appropriate value of the Voigt a parameter is taken from Mitchell and Zemansky[7]. The computed sodium atom densities, given in Figure 2, are used in the model to compute the flame optical thickness. The physical flare size is estimated from photographic records.

When the radiative transfer equation containing all the necessary inputs is solved, we obtain a spectral radiant power distribution which can be compared to the experimental spectra. Examples of some of these spectra are compared in Figure 3 for Group 26 formulations. Visual inspection of these spectra shows that the theoretical spectra on the right have nearly the same spectral distribution as the experimental spectra on the left.

Experimental and theoretical values of delta lambda, the distance in Angstroms from the sodium D_2 line center to its blue maximum, are also compared in Figure 3. The agreement between these values is also considered acceptable. Other tests for agreement between the theoretical and experimental spectra will be reported as the work progresses.

Concluding Remarks

The model is being tested over a wide range of pressure and sodium atom density. It appears that the agreement between theory and experiment will turn out to be good enough for one to conclude that the model is valid, making it useful in its present form for predicting the output of a large variety of pyrotechnic flares.

References

1. B. E. Douda, R. M. Blunt, and E. J. Bair, "Visible Radiation from Illuminating-Flare Flames: Strong Emission Features", J. Opt. Soc. Am. 60, 1116-1119 (1970).

2. B. E. Douda and E. J. Bair, "Visible Radiation from Illuminating-Flare Flames. II. Formation of the Sodium Resonance Continuum", J. Opt. Soc. Am. 60, 1257-1261 (1970).

3. B. E. Douda, "Atlas of Radiant Power Spectra of Four Flare Formulas at 8 Levels of Ambient Pressure", RDTR No. 205, NAD Crane, Indiana 47522 (June 1970). Available from National Technical Information Service, 5285 Port Royal Road, Springfield, Virginia 22151. AD# 746123.

4. B. E. Douda, "Pyrotechnic Flare Spectroscopy II", RDTR No. 206, NAD Crane, Indiana 47522 (June 1970). Available from National Technical Information Service, 5285 Port Royal Road, Springfield, Virginia 22151. AD# 746124.

5. The computer code described in NASA SP-273, entitled "Computer Program for Calculation of Complex Chemical Equilibrium Compositions, Rocket Performance, Incident and Reflected Shocks, and Chapman-Jouguet Denotations", S. Gordon and B. J. McBride, NASA Lewis Research Center, Cleveland, Ohio, 1971, was used to compute the adiabatic temperature and equilibrium distribution of reaction products at that temperature. The ratio of gaseous atomic sodium mole fraction to mole fraction of all gaseous species is β, the atomic sodium partial pressure being $[P \cdot \beta]$. The sodium atom density D is estimated by $D = n/V = [P \cdot \beta]/RT$ where n is the number of particles, V is volume, P is ambient pressure, R is the ideal gas constant, and T is the adiabatic temperature.

6. J. T. Jefferies, "Spectral Line Formation" (Blaisdell Publishing Co., Waltham, Massachusetts, 1968), p. 17.

7. Allan C. G. Mitchell and M. W. Zemansky, "Resonance Radiation and Excited Atoms" (Cambridge University Press, Cambridge, Massachusetts, 1971), p. 174.

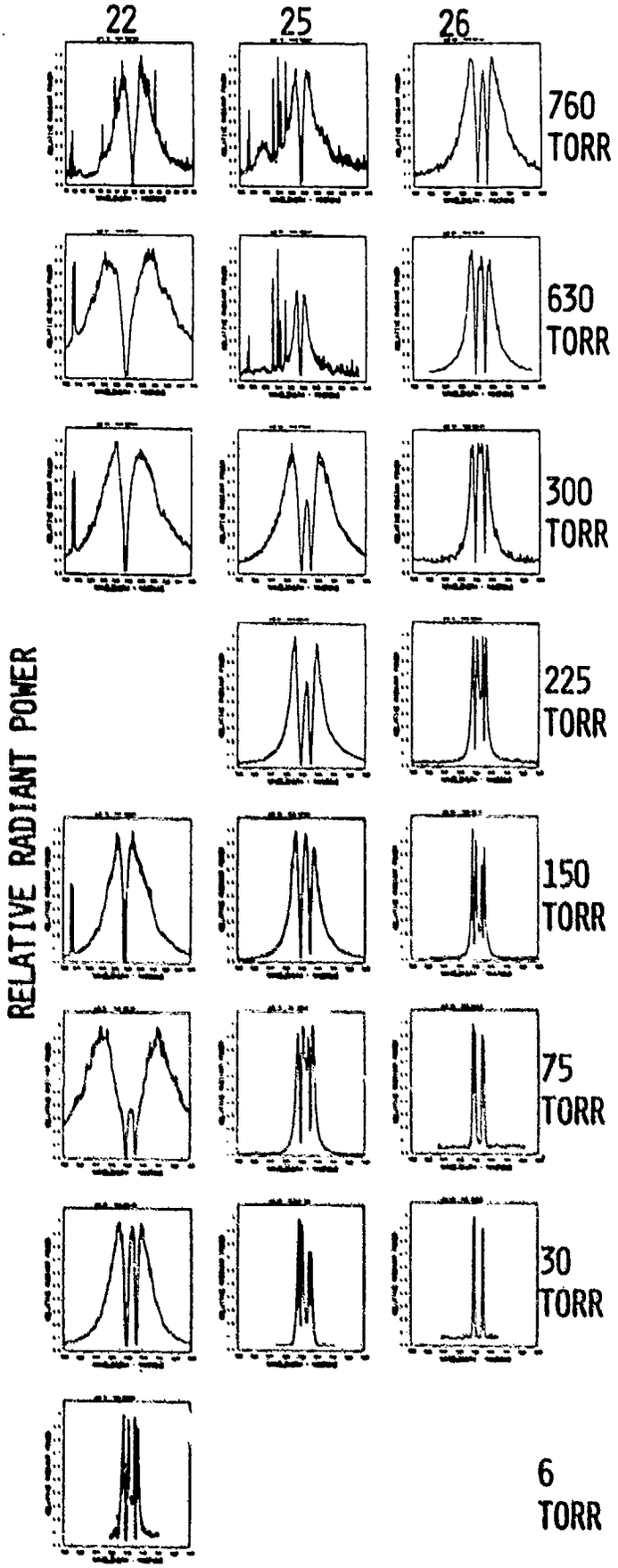

Figure 1. Relative radiant power spectra in the visible region of three illuminating flame formulas (Groups 22, 25, and 26) at ambient pressures between 760 and 6 torr.

MAGNESIUM NANO3 KNO3 BINDER PRESSURE	44.0 51.5 - 4.5 GROUP 22	40.4 5.15 49.95 4.5 GROUP 25	40.04 0.515 54.945 4.5 GROUP 26
760	2939 1.01×10^{18}	2905 1.10×10^{17}	2904 1.11×10^{16}
630	2920 8.46×10^{17}	2887 9.20×10^{16}	2886 9.26×10^{15}
300	2842 4.08×10^{17}	2816 4.44×10^{16}	2815 4.47×10^{15}
225	2812 3.08×10^{17}	2788 3.34×10^{16}	2787 3.37×10^{15}
150	2770 2.07×10^{17}	2748 2.24×10^{16}	2747 2.26×10^{15}
75	2698 1.05×10^{17}	2680 1.14×10^{16}	2679 1.15×10^{15}
30	2606 4.29×10^{16}	2592 4.65×10^{15}	2591 4.67×10^{14}
6	2453 8.90×10^{15}	2443 9.63×10^{14}	2442 9.70×10^{13}

Figure 2. Computed adiabatic reaction temperature (upper number in °K) and sodium atom density (lower number, atoms/cm^3) for three illuminating flame formulas (Groups 22, 25, and 26) at ambient pressures between 760 and 6 torr. Thirty percent enthalpy loss is assumed.

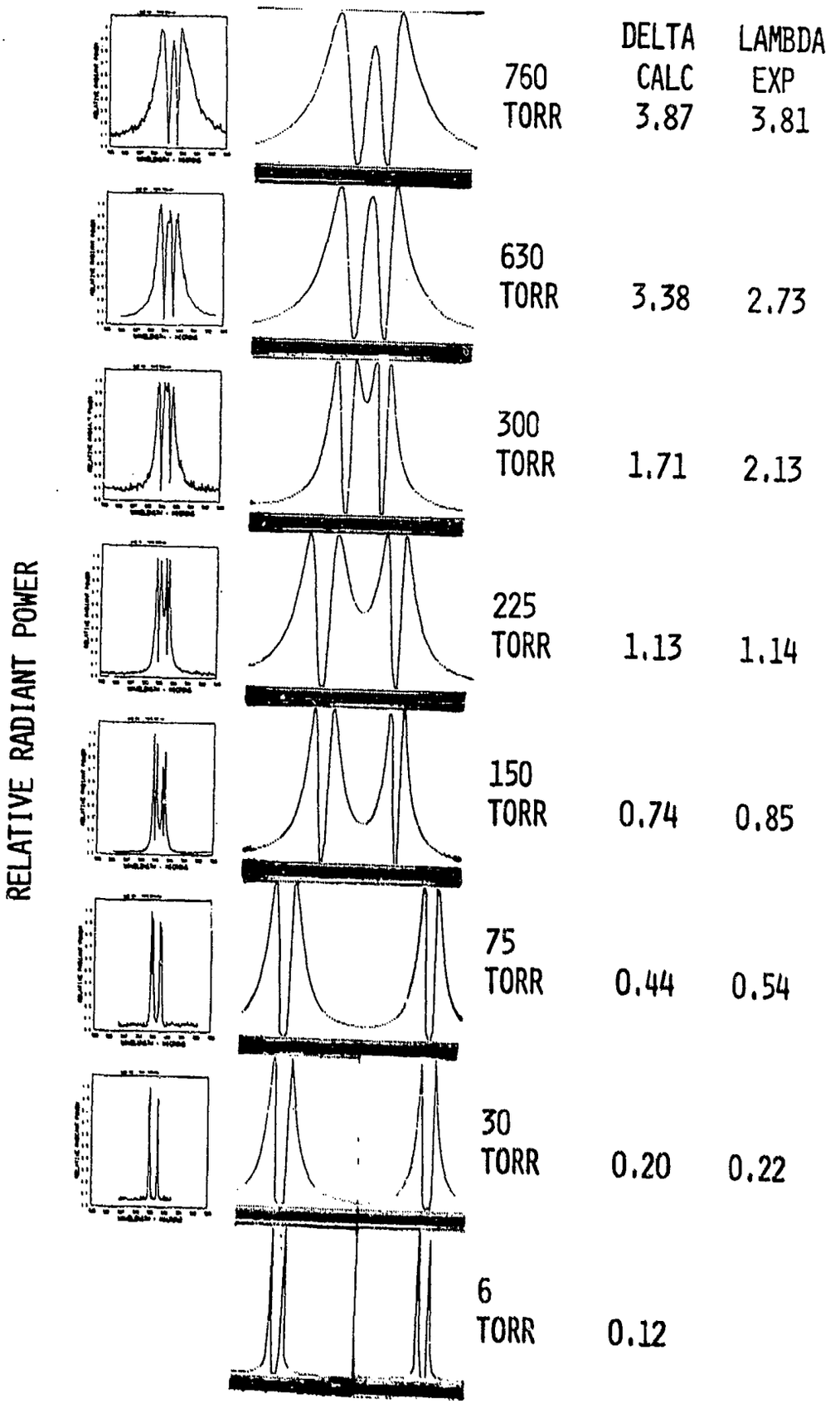

Figure 3. Comparison of experimental radiant power spectra (left column) at pressures between 760 and 30 torr to theoretical spectra (right column) computed by using an LTE radiative transfer model. Experimental and theoretical values of delta lambda, the distance in Angstroms from the sodium D_2 line center to its blue maximum, are also computed.